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West Point, New York 10996

Improve Ballistic Test and Evaluation Methodology

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Ballistic test and evaluation of body armor is of great priority for the US Army to meet current operational needs. The current experimental design process centers on standardized threat level classifications and a baseline ballistic limit velocity, V50; both measures originate from the National Institute of Justice circa 1979. The measures are complex, statistical in nature, and yield large quantities of data. A methodology incorporating response surface techniques improves ballistic test and evaluation from a pass fail analysis of data to iterative, directional experiments with design intelligence. Without this mathematical direction, it is extremely difficult to analyze the multitude of factors and their interaction effects in order to attain product improvement. We provide a ballistic experimental design example to demonstrate the usefulness of this methodology and identify the potential for its application in future armor developments.

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Abstract

Ballistic test and evaluation of body armor is of great priority for the US Army to meet current operational needs. The current experimental design process centers on standardized threat level classifications and a baseline ballistic limit velocity, V50; both measures originate from the National Institute of Justice circa 1979. The measures are complex, statistical in nature, and yield large quantities of data. A methodology incorporating response surface techniques improves ballistic test and evaluation from a pass fail analysis of data to iterative, directional experiments with design intelligence. Without this mathematical direction, it is extremely difficult to analyze the multitude of factors and their interaction effects in order to attain product improvement. We provide a ballistic experimental design example to demonstrate the usefulness of this methodology and identify the potential for its application in future armor developments.

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This project incorporates the expert knowledge of scientist Dr. James Zheng, Program Director of Soldier Equipment for PEO Soldier. His knowledge the experimental design process assisted in the development of this methodology. Additionally, LTC John Halstead, Ph.D. provided the mathematical knowledge and digital code for the Response Surface portion of this project.

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Chapter 1: Introduction

Current experimental design methodology utilized by Army researchers and armor industry material scientists primarily determines the effectiveness of a given armor design. The scientists' mission is to develop body armor systems that are effective in defeating multiple threats under various environmental conditions, minimize weight, maximize comfort and utility, and perform consistently within published specifications. Scientists must consider a myriad of factors including material, areal density, composition, weave, resins, production methods, and a continuously growing list of others. In addition, they must measure performance in meeting specifications for standard threat level classifications, pass-fail penetration for multiple round types, statically based velocity thresholds for multiple round types, and other vital experimental responses. This complex experimental environment requires both expert knowledge and a large number of design points, especially to maintain accuracy in evaluations for protecting human life.

Decision makers receive data from multiple ballistic laboratories, organized in batches that cause analytical comparisons and multivariable analysis particularly troublesome. The decision maker relies on expert knowledge and intimate familiarization with the data to make recommendations for further system enhancement or future directional design iterations.

A change in current methodology would offer the decision maker intelligent design by providing surface response, factor reduction, and an easily adaptable, flexible process to evaluate, analyze, and improve armor systems design.

Chapter 2: Proposed Methodology

2.1 Response Surface Techniques

Response Surface Methodology (RSM) is documented by Myers and Montgomery as "a collection of statistical and mathematical techniques useful for developing, improving, and optimizing processes." The experimental design can include any number of factors and responses. The factors are encoded to achieve orthogonal design using the transformation equation $x_i = \left(\xi_i - \left(\frac{\xi_{iLow} + \xi_{iHigh}}{2}\right)\right) \Big/ \left(\frac{\xi_{iLow} + \xi_{iHigh}}{2}\right)$ The result of this transformation is the

functional approximation $E[y] = f(x_1, x_2, x_3 ..., x_k)$. A preliminary experiment, called a screening experiment, investigates the statistical importance of these factors in hopes of reducing the design by eliminating the unimportant ones. Table 1 is a design example of the natural variables that would result from a preliminary experiment, including in-significant factors.

TABLE I

Factor Levels

	Level	
Factors	**Low (-)**	**High (+)**
Factor A	Value	Value
Factor B	Value	Value
Factor C	Value	Value

The actual experimental design includes all necessary factor combinations, including interactions, much like the example in the Table 2.

TABLE 2

Experimental Design

Design	**Factor A**	**Factor B**	**Factor C**	**Response**
(1)	-1	-1	-1	Value / Binomial
A	1	-1	-1	
B	-1	1	-1	
AB	1	1	-1	
C	-1	-1	1	
AC	1	-1	1	
BC	-1	1	1	
ABC	1	1	1	

The experiment is orthogonal in design, providing powerful least squares regressions within a small order region of experimentation in a given multivariable space. The standard form logistic regression function is $\hat{y} = b_0 + b_1x_1 + b_2x_2 + ... + b_kx_k = B^{\mathrm{T}}x$. In order to achieve this function with the orthogonal design used in this methodology, we first have to achieve linear regression through log odds. This logit function shows the probability x=1 in a given distribution

$\Pi(x) = \Pi(x=1) = \frac{\exp^{\beta^T x}}{1+\exp^{\beta^T x}}$, and the probability x = 0 is $\Pi(1-x)=\Pi(x=0)=1-\Pi(x=1)=\frac{1}{1+\exp^{\beta^T x}}$. This summarizes into one equation for the odds of an event x given as $O(x) = \frac{\Pi(x)}{1-\Pi(x)} = \exp^{\beta^T x}$. Taking the natural log of these odds and you return to the standard logistic regression of beta matrix transposed x shown as $\ln[O(x)] = \ln[\exp^{\beta^T x}] = \beta^T x$. When the design matrix requires the use of a binomial response, such as whether or not a round penetrated an armor material or simply met a given standard, the design requires a mathematical model known as a logit link. In RSM the logistic regression function is essentially attempting to achieve a mean, or expected, value.

The relationship is shown mathematically as $E[y]=\mu\approx\hat{y}=f(x)=b_0+b_1x_1+b_2x_2+...+b_kx_k=B^Tx$. If this is true, then $E[y]=B^Tx$. Because we know in a binomial response $y\in[0,1]$, we know values cannot exist between y and 0. This requires we transpose B^Tx with the logit link $\ln E[y]=\ln\mu=B^Tx\Rightarrow\mu=e^{B^Tx}\Rightarrow odds\Rightarrow\ln[\frac{\mu}{1-\mu}]=B^Tx$. Even with a binomial response, the mathematics return to the original logistic regression of beta matrix transposed x with this logit link.

The benefit of linear regression is that reduces design points and allows for multifactor design through an iterative process that searches for a near optimum using the method of steepest ascent or decent. If multiple responses exist, the scientist can superimpose response surface contours into more complex process optimization problem or develop a binomial response from standards based performance specifications that will utilize the logit link model shown above. Special consideration in the experimental design can also reduce variability from noise factors through robust parameter design.

2.2 Iterative Process

The iterative process this methodology incorporates with RSM includes a repetitive sequence of conjecture, design, experiment, and analysis. This sequence is only constrained by the conjecture and the experiment. Additionally, the sequence does not move linearly, meaning conjuring can begin prior to completion of the first phase of analysis. The subsequent design will incorporate the information of the first along with the conjecture. This cycle repeats as long as

necessary to reach the objective of the design process. Box and Draper depict this iterative process in Figure 1.

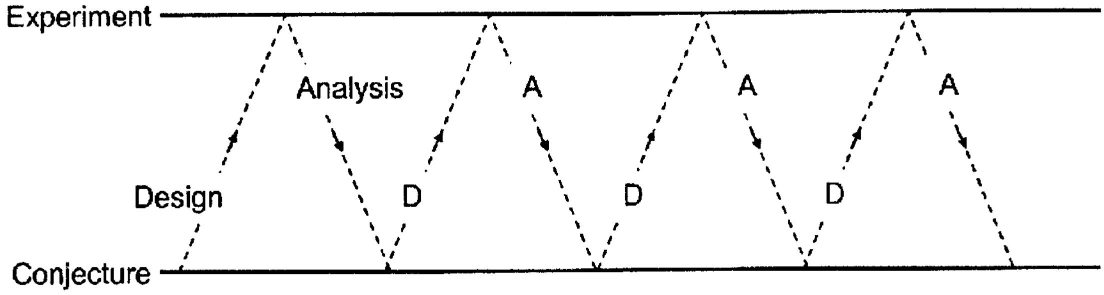

Figure 1: The Iterative Nature of Experimentation, illustrates the process of design, experimentation, analysis, and redesign (Box and Draper, 1987).

RSM follows this iterative process that begins with fitting a first order plane or some other multi-dimensional model using orthogonal design. In the first experiment, or screening experiment, interaction effects are considered using second order equations and conducting an analysis of variance (ANOVA) to determine if the p-value for each factor is significant based on a given confidence interval. If the factors are not statistically significant, then they are eliminated from the experimental design. The next step is to find the path of steepest ascent or descent by conducting single or replicated runs of the experiment based on the variables in the design for the given region of interest. The experimental region, including the fit of a new multidimensional model, is centered on a point along the path of steepest ascent or descent as a base for a second experiment. The experiment continues in this process until response indicates a near optimum system or a holistic objective has been achieved.

Chapter 3: Applied Experiment

3.1 Purpose

The purpose of this example experimental design is to demonstrate the usefulness of the methodology and the feasibility of its application in ballistic experiments. The factors in this model are simulated and the computer-generated results are typical of those used by scientists and product developers. Ballistic scientists can utilize this example to easily tailor an experiment to their strategic goals given their complex list of factors, responses, and objectives.

3.2 *Factor Design*

In order to demonstrate the usefulness and feasibility of this methodology we designed a simulated experiment analyzing two materials of ballistic armor for use in Outer Tactical Vests (OTV). These vests are carriers composed of soft body armor, providing protection from small arms and shrapnel. The OTVs also carry Small Arms Protective Inserts (SAPI) and are used to affix equipment to the soldier's body. We developed a model to simulate data in order to drive a typical experiment that can show usefulness of this methodology. The simulated data both protects the sensitive nature of the actual material and also helps to better communicate usefulness of the methodology. We included three factors which are material, aramid fiber weave design, and areal density. These particular factors are representative of typical considerations for soft body armor experimentation, but they can be anything of importance to the decision maker. Designing the experiment in this manner will compel product improvement because it focuses on differentiating the materials through type, composition, production processes, weight, and more. The example experimental design is shown in Table 3.

TABLE 3

Applied OTV Experiment

	Level	
Factors	**Low (-)**	**High (+)**
Material	Type 1	Type 2
Areal Density	1.05 psf	1.10 psf
Weave Design	29x29	32x32

3.3 *Response*

It is important to understand that in ballistic experiments, the client must fire a large number of shots to determine accurate levels of performance. As with anything there is some amount of variability in the sample. Figure 2 illustrates that for a given armor material, it will perform consistently within a within its intended range of use; however, soldiers may experience impacts beyond the intended level of threat protection in the zone of mixed results. In this graph, the material performs consistently well at a given velocity V0 and consistently poor at a velocity greater than V100.

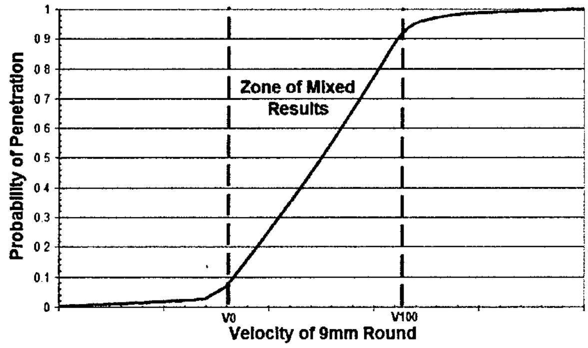

Figure 2: Statistical Ballistic Response, illustrates the zone of mix results that requires special consideration to ensure accurate evaluation of armor performance.

Response surface methodology will allow the client to analyze a large quantity of data to determine performance within the zone of mixed results and drive future experiments to improve the system. One advantage of this methodology is the ability to analyze a binomial response, whether it is a pass-fail penetration check or even the ability to determine if a material passed a given list of standards beyond just penetration. This response can significantly simplify large amounts of data, while retaining intelligent design features. The response for this simulated experiment is a binomial variable called penetration.

Chapter 4: Results of the Experiment

4.1 Significant Factors

The first step in analysis of this experiment is to organize the data into an orthogonal design with a large enough sample size to ensure the accuracy of response, especially considering its statistical nature. Analysis of variance shown in Table 4 identifies factors A and B, as well as the interaction between factor A and B, as the statistically significant factors in the experiment.

TABLE 4

Analysis of Variance

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
A	1	0.99488	0.99488	81226.15	< 2e-16
B	1	0.31841	0.31841	25996.6	< 2e-16
C	1	0.00005	0.00005	3.7396	0.05348
A:B	1	0.17091	0.17091	13953.81	< 2e-16
A:C	1	0.00002	0.00002	1.594	0.20711
B:C	1	0.00001	0.00001	0.5035	0.47818
A:B:C	1	2.52E-06	2.52E-06	0.2058	0.65017
Residuals	832	0.01019	0.00001		

In this experiment factor C, the aramid fiber weave design, does not affect the response and can be eliminated from analysis. The significance of these factors and their interactions can be communicated in a normal plot of effects as illustrated in Figure 3. Notice the deviation of significant factors A, B, and the interaction of A and B.

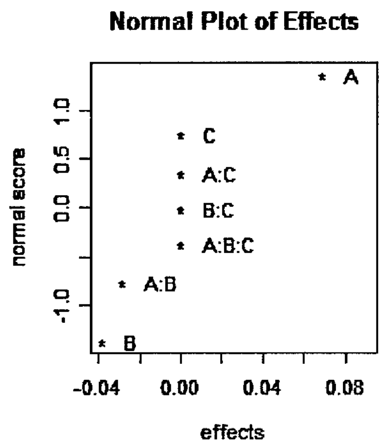

Figure 3: Normal Plot of Effects, illustrates which factors are significant.

4.2 Response Surface

Once the design is complete and significance is determined, a response for the significant factors is easily computer-generated. In this case, a three-dimensional surface is required to show interactions between factors A and B. Another experiment may require multiple surfaces to

simplify a multivariable problem with additional significant factors. Unfortunately, we cannot illustrate a response beyond a third dimension. The response surface for this experiment is show in Figure 4.

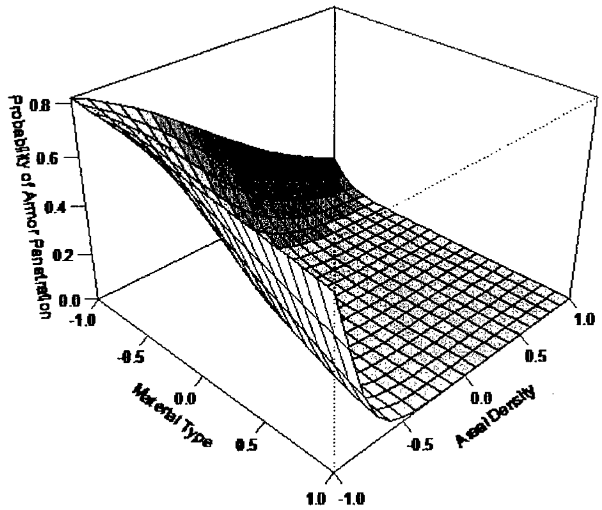

Figure 4: Response Surface of Body Armor illustrates the response of the experiment with respect to factors A and B.

4.3 Analysis and Application of the Response Surface

This experiment illustrates a very distinct relationship between the probability of penetration and the factors material type and areal density. This is a minimization problem, attempting to minimize the probability of penetration, so the direction of steepest *descent* toward material type 2, the binomial high value of Factor A in the experimental design, and the high value of areal density.

The response demonstrates the usefulness of the methodology because it illustrates how clearly the decision maker can determine the parameters for the next iteration of experimentation. This response indicates the next experiment should include material more like material two and a higher areal density in order to achieve and even smaller response. However, this experiment also indicates the high values of the factors already reached zero probability of penetration, so no further experiment is required. Had the lowest probability achieved been greater than zero, this iterative process of experimentation could continue until the experiment yields a near optimal response.

In this case, the scientist may want to design an experiment with an areal density between the high and low value of the current experiment in order to determine the response of lighter material. This next experiment would be an effort to find an acceptable probability of penetration at the lowest weight, a tradeoff extremely important to body armor design.

Chapter 5: Conclusion

This experiment demonstrates the usefulness of this methodology to the armor industry, but it relies on the expertise of armor specialists to bridge the gap between data simulation and reality. It will require scientists to develop similar experimental designs, but allow the flexibility of this methodology to encompass the factors and responses inherent to their unique problems. The design will drive needed coordination between scientists and producers to develop the many variations the armor system necessary to carry out the experiment. The process is simple, but the results are far reaching. The iterative experimental design process will follow a direction of intelligent design, and the statistical nature of methodology will ensure accuracy of the response within the zone of mixed results. In short, this improved ballistic test and evaluation methodology can result in a better product and safer performance evaluation. It is ultimately beneficial to decision makers, product developers, and of course the soldiers they protect.

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Appendix A: List of Abbreviations

A	
ANOVA	Analysis of Variance
O	
OTV	Outer Tactical Vest
R	
RSM	Response Surface Methodology
S	
SAPI	Small Arms Protective Insert
U	
USMA	United States Military Academy

*This table is sorted alphabetically

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